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Developments And Activities In Solar Sail Propulsion

Charles Garner and Humphrey Price
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

David Edwards and Randy Baggett
NASA Marshall Space Flight Center
Huntsville, Alabama 35812

ABSTRACT

NASA's drive to reduce mission costs and accept the risk of incorporating innovative, high payoff technologies into its missions while simultaneously undertaking ever more difficult missions has sparked a greatly renewed interest in solar sails. From virtually no technology or flight mission studies activities three years ago solar sails are now included in NOAA, NASA, DOD, DLR, and ESA technology development programs and technology roadmaps. NASA programs include activities at Goddard Space Flight Center, Jet Propulsion Laboratory, Langley Research Center, and Marshall Space Flight Center. Solar sail demonstration missions are under study at NASA, NOAA-DOD, Carnegie-Mellon University and DLR/ESA, and Team Encounter and the Planetary Society plan to fly solar sails. This paper summarizes these on-going developments in solar sails.

Introduction

Solar sails and large ultra-light apertures have crosscutting benefits to many NASA enterprises. NASA's Office of Space Science has developed four major themes for space exploration and a portrait of missions that are representative of the key technological challenges and scientific objectives that must be addressed. Two of these themes, Exploration of the Solar System (ESS) and the Sun-Earth Connection (SEC), have identified solar sail propulsion as a technology that will enable or enhance portrait missions. Missions in the SEC that can potentially be enabled or enhanced are the Solar Polar Image, Space Weather Sentinels, and the first generation Interstellar Probe launched to explore the outer reaches of the solar system. Several SSE roadmap missions such as Neptune and Europa Orbiters or Titan Explorer, and sample return missions can also benefit from sails. Sails may be used in the future as occulters for Astronomical Search for Origins (ASO) and Structure and Evolution of the Universe (SEU) missions and as orbit propulsion for Earth Science. Sails can also deliver cargo for human exploration of Mars.

The concept of solar sailing was first envisioned in science fiction in 1889[1]. Tsiolkovsky[2] proposed in 1924 that large spacecraft could be propelled through space using photon pressure, and in the same year Fridrikh Tsander[2] proposed the lightweight solar sail design that is discussed today-a metallized plastic film.

The technical challenges in solar sails are to fabricate sails using ultra-thin films, deploy these structures in space, and control the sail/spacecraft. For reasonable trip times the sail must be very lightweight-from 20 g/m^2 for missions that could be launched in the near-term to 0.1 g/m^2 for far-term interstellar missions. Modern sail designs make use of thin films of Mylar or Kapton coated with about 50 nm of aluminum with trusses and booms for support structure. The thinnest commercially-available Kapton films are 7.6 μm in thickness and have an areal density (defined as the total sail mass divided by the sail area) of 11 g/m^2. A propulsion trade study[3] performed in 1998 identified the benefits and sail performance required to provide significant advantages over other propulsion technologies. The Study concluded that sails with areal densities of about 10 g/m^2 are appropriate for missions such as a Mercury Orbiter or small spacecraft positioned between the sun and the earth. More far-term missions such as an Asteroid Rendezvous/Sample Return require sails with an areal density of 5-6 g/m^2 and films with a thickness of approximately 1-2 μm. More advanced missions require sails with areal densities of under 3 g/m^2 for positioning spacecraft in non-Keplerian orbits or 1g/m^2 for fast trip times to 200 AU[4].

Recently NASA has encouraged programs to reduce the size and mass of spacecraft used for robotic exploration of the solar system[5-6]. Spacecraft with masses below 100 kg are being studied for performing challenging missions, and microspacecraft technology is being developed that may result in robotic spacecraft with masses of 10 kg or less[7]. Solar sail propulsion is synergistic with the new NASA approach to accomplish missions cheaper because the use of solar sails allows the use of smaller, cheaper launch vehicles. Solar sails have been studied in the literature for decades as a novel propulsion system for planetary and interstellar missions. Solar sail propulsion could enable missions never considered possible[8-11], such as non-Keplerian orbits around the earth or sun, or exciting commercial applications, such as polar communication satellites.

Progress in developing ultra-thin materials and lightweight carbon-fiber structures has made solar sails a feasible technology for high delta-velocity missions to Mercury, the outer planets and the local interstellar medium. Programs whose goals are to make solar sails a reality are now in place or planned. Activities include mission studies, technology developments, and space validation missions.

The European Space Agency (ESA/ESTEC), the German Aerospace Center (DLR), NASA's Office of Space Science (Code S) and NASA's Aerospace Technology Enterprise (Code R) have either initiatives or programs in place to support the development of solar sails. NASA programs include activities at Goddard Space Flight Center (GSFC), Jet Propulsion Laboratory (JPL), Langley Research Center (LaRC), Marshall Space Flight Center (MSFC), and the NASA Institute for Advanced Concepts (NIAC). There are National Oceanic and Atmospheric Administration (NOAA) and Department of Defense (DOD) activities as well. Finally, the Planetary Society plans two solar sail technology validation missions for 2001, and Encounter plans to use solar sails for primary propulsion for it's mission beyond our solar system. This paper summarizes solar sail state-of-art, technology developments, mission architecture studies, and ongoing flight mission activities.

I. NASA Programs Supporting Solar Sails

There are programs to support solar sails at NASA GSFC, JPL, LaRC, MSFC, and the NIAC. Both Code R and Code S are supporting sail technology developments, mission studies and mission analysis. These supporting programs are summarized below.

I (a). LaRC activities

I (a.1). Solar Sail Ground Testbeds

The objective of this program is to develop a 1/5 to 1/4 scale model of a 40-50 m class, 10-20 g/m^2 solar sail for ground based deployment testing and structural characterization using a four boom, square sail configuration. A mission requirements document is being developed for a pseudo mission similar to the NOAA/NASA GEOSTORM mission. This requirements document will flow down the full scale properties of the sail booms and membranes. Geometric scaling will be used to develop three10 m solar sail testbeds. The first testbed is a single boom - 2 quadrant (SB2Q) system that deploys a boom vertically while unfurling two quadrants of sail membrane. The SB2Q testbed will be used to study boom deployment forces and moments, membrane to boom interfaces to minimize wrinkling of the sail, and new ultralight boom deployment systems. The second testbed is based on constant thickness scaling (Mikulas et. al.). Due to the limitations of minimum gage scaling, this static constant thickness scaling (SCTS) testbed will not incorporate deployment mechanisms. It will be fabricated in the deployed shape and used to validate mechanics and dynamics analysis models. The SCTS testbed will be tested vertically in a 16 m vacuum chamber. The 16m vacuum chamber at the NASA Langley Research Center has been recently upgraded to test and characterize ultralightweight spacecraft components and subsystems using optical techniques such as photogrammetry and laser vibrometry. The last ground testbed is a deployable geometrically scaled (DGS) model. The DGS testbed will be used to evaluate deployment risks of various boom/sail deployment systems. Deployments will occur in vacuum in a vertical orientation. Gravity counter-balance devices will be used at the boom tips.

Gound testing of deployment concepts for a four boom, square sail configuration must be performed to gain confidence in the deployment mechanics and dynamics. Measurements made during deployment, rigidization, and also in the subsequent structural characterization tests will be used to assess the degree of predictability of solar sail structural performance. Test data will be correlated with deployment and structural analysis models to validate these analysis tools for full scale design. This is a multi year effort with most of the deployment testing occurring in FY-2002. The SB2Q testbed is being fabricated and initial testing is to commence in the summer of 2001. Also in 2001, the booms and membrane material properties for the SCTS testbed will be baselined using the mission requirements document described above. In 2002, all components including test measurement equipment for the SCTS and DGS testbeds will be acquired and assembled. Subsequent to deployment and rigidization, extensive structural mechanics and dynamics tests will be performed to acquire a sufficient database for analysis model validation.

I (a.2). Rigidizable Column Testing

The objective of this program is to develop test validated analysis models of deployable/rigidizable columns in order reliably predict the mechanics, dynamics and thermal response of future solar sail support structures. A number of test specimens of differing lengths, types (tube, isogrid) and of various rigidization methods will be evaluated, including thermosets, thermoplastics, UV cured, and shape memory elastics. This task leverages significant database development for thermoset and thermoplastic columns previously supported by the cross-enterprise technology program. Static and dynamic test procedures have been developed and cross-checked for accuracy. New in the test matrix are columns with isogrid geometry and those made of UV cured materials and elastic memory materials. Both short (L/D = 10) and long (L/D=100) columns will be tested and modeled. In-situ characterization aims to provide minimally invasive self contained sensing systems that will provide all data needed to validate analytical models for future solar-sail designs. This coordinated test and analysis program will provide a means to advance the technology readiness in an unbiased manner.

This technology is enabling for future solar sail missions. The support structures dominate the performance efficiency of solar sails (mass, sail wrinkling, static, dynamic, and thermal deformations). A number of promising candidate material systems are in low TRL. These columns are known to have imperfections due to geometric distortions, rigidization at only 20-28 kPa (3-4 psi), incomplete curing, packaging damage, etc. Critical test data needed to characterize the tubes will be identified through this ground test/analysis task such that an in-situ characterization system for zero-g (flight) experiments can be developed.

The three elements of the study began in FY-01. The first element is to analytically model deployable and rigidizable columns using state-of-the-art finite element codes to predict the mechanical, dynamic and thermal response. The second part is to conduct a test program to characterize the structural behavior of the inflatable-rigidizable columns, which will be used to verify the data generated in the analytical modeling and parametric study. The third aspect is to develop in-situ sensing for future flight experiments using aspects of multifunction structures. The test program, in-situ sensing, and the modeling efforts will be conducted simultaneously. Thirteen column types have been tested in FY-01. Various isogrids, trusses, and long columns are being instrumented for testing in early FY-02 (Figure 1).

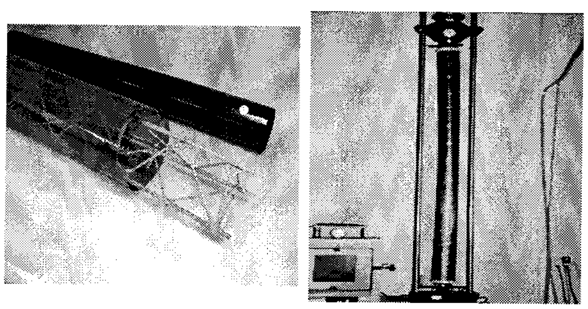

Figure 1(a). Isogrid and inflatable booms.

I (a.3). Solar Sail Materials Development Projects

The objective of the in-house materials activity is to develop ultrathin (less than 7 microns) polymer membranes with the proper combination of properties for use as solar sails to meet near term (40m class, 10-20 g/m2) and long term (100m class, 5-10 g/m2) mission requirements.

The approach involves the integration of several materials technologies into a single, space environmentally durable, polymeric material. These include in-situ metallization, additives to improve radiation, tear resistance and handlability, incorporation of electrical conductivity for static charge mitigation and improvements in ultrathin film processing.

The product from this work will be a thin film material that can meet the performance requirements for solar sail based missions. Other applications for this material may be found in microelectronics or other high technology areas. Another product of this work will be a materials property database and a better fundamental understanding of thin film fabrication methods and structure/property relationships.

This work is complimented by several externally funded activities. One is a phase I SBIR with Physical Sciences, Inc. (NAS1-01048) to investigate the feasibility of manufacturing sails in space. There are two other activities funded under NASA Research Announcement NRA 99-OSS-05. One is with SRS Technologies (Huntsville, AL) that is focused on the fabrication of a prototype solar sail from space environmentally durable polymers. The other is with Physical Sciences, Inc. (Andover, MA) where the focus is to fabricate novel rip-stop material technology that is compatible with space environmentally durable, ultra-thin polymer films.

I (a.4). Gossamer Spacecraft Initiative

The Gossamer Spacecraft Initiative is a new NASA Code S program to begin long-range development of enabling technologies for very large, ultra-lightweight structures and apertures. Gossamer spacecraft technology will eventually allow NASA to undertake bold new missions of discovery, such as searching for the signs of life on planets orbiting nearby stars, and sailing beyond our solar system on beams of light. This program, managed for NASA by LaRC, seeks to achieve NASA's long-range goals by developing radically different observatories and spacecraft to achieve breakthroughs in mission capability and cost, primarily through revolutionary advances in structures, materials, optics, and adaptive and multifunctional systems.

The Gossamer Spacecraft will support sail development through focused technology developments and NASA Research Announcements (NRA). In FY 2001 the Gossamer NRA funded 9 winning sail-related NRA proposals[16] at a total funding level of approximately $3M that substantially increased the level of funding for the development of solar sail technologies. Technologies to be developed under the NRA include innovative sail architectures such as "dusty plasmas", hoop and microwave-driven sails, advanced sail films including multi-functional membranes, nano-structured films, and sublimating films, advanced inflatable and isogrid booms, and advanced solar sails for attitude control of spacecraft. Some of these winning proposals may be funded for

I (b). MSFC Sail Programs

I (b.1). Advanced Space Transportation Program

The Advanced Space Transportation Program (ASTP) at MSFC is responsible for managing solar sail technology under NASA's Space Science Enterprise (Code S) as a part of the "In-Space Propulsion (ISP)" technology program. Beginning in FY02, the ISP will focus on technology products and ground demonstrations that will enable future NASA missions, including solar sail technology. The ISP program plans to release an NRA in the Fall of 2001 to address multiple propulsion technologies.

Future solar sails technology solicitations will investigate system design concepts and demonstration of prototype solar sail systems technologies needed to enable these design concepts; leading to future validation of the solar sail systems technology through simulation and ground tests.

I (b.2). Solar Sail Technology Working Group

In FY 2001 MSFC began supporting a program focused on solar sail technology development in

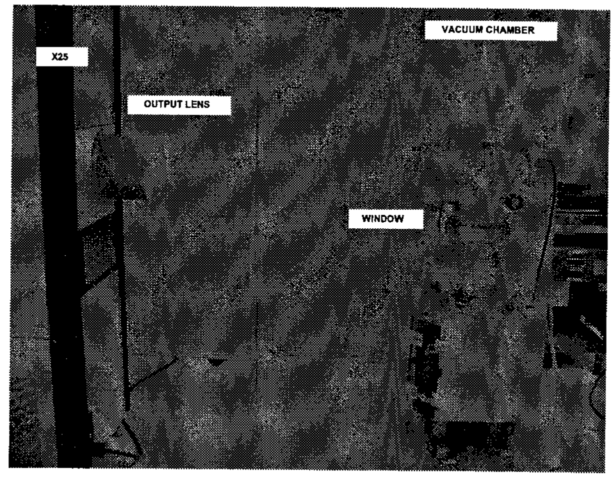

Figure 2. Photon Pressure Measurement System

collaboration with the Gossamer Spacecraft Initiative. The program at present included the creation of a multi-center Solar Sail Technology Working Group whose charter is to identify technology paths and development programs, and develop the technology roadmaps and milestones required to meet the needs of the many customers for the technology.

I (b.3). Advanced Propulsion Concepts Program

MSFC continues to support sails through it's Advanced Propulsion Research Project, which is responsible for the development of advanced space propulsion technologies in ASTP. This project supports research in solar sails at JPL, MSFC, and universities.

I (b.4). MSFC In-House Activities

In-house activities at MSFC to support solar sails in FY 2001 include characterization and testing of ESLI's revolutionary carbon fabric, photon/material interaction physics modeling and laser/sail material interaction studies, physical properties measurements of various ultra-thin-films, and space testing of thin films on the Materials for International Space Station Experiment (MISSE) flight test. The Space Environmental Effects Team developed the testing capability to measure photon pressure on candidate sail material. Initial proof of concept measurements were reported in a recent AIAA paper[17]. The measured value of photon force was within 7% of the theoretical calculated value. After these proof of concept measurements were obtained, modifications to the test system were initiated. The primary modification increased the test chamber volume to accommodate a larger sample size. The original test system, shown in figure 1, utilized an active measurement area of 109.5 cm^2. With the new test chamber, a sample active area of 214 cm^2 can be evaluated. These modifications are scheduled to be complete by July 2001 and candidate sail material photon pressure measurements will begin. The Space Environmental Effects Team at MSFC has received various types of material for photon pressure measurement. These materials are 2.5 micron aluminized Mylar™, 3 micron metalized CP1, and 0.9 micron metalized Mylar™.

Figure 2. Photon Pressure Measurement System

The Space Environmental Effects Team at MSFC continues Space Environmental Effects testing and characterization of candidate solar sail material. These sail materials are exposed to an equivalent exposure to a Geosynchronous Transfer Orbit (GTO). The sail material currently being evaluated is 2.5 micron Mylar™ with 50 nm of aluminum coated on both sides of the Mylar™. Mechanical property and thermo-optical data were obtained after a 1 month, 2 month, and 6 month equivalent exposure in a GTO environment. This data is shown in figures 3 and 4.

The GTO exposure consisted of electron irradiation at 5, 12 and 50 KeV electrons. Fluence levels of each energy were varied to produce the required dose level for the 1 month, 2 month and 6 month equivalent GTO exposures. Results on the evaluation of metalized 0.9 micron Mylar™ will be available in the fall of 2001.

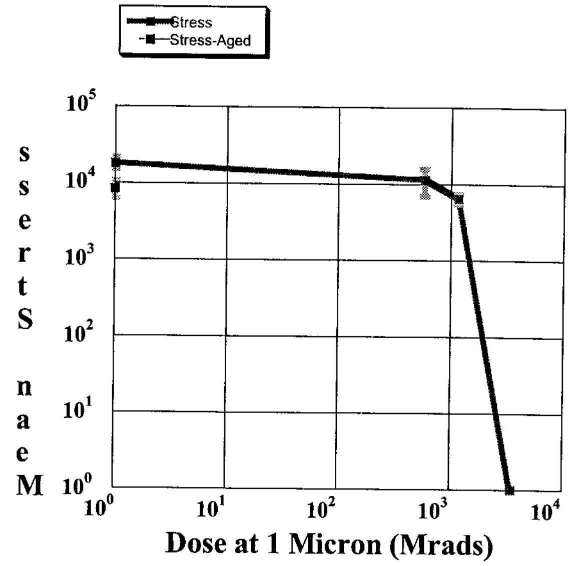

Figure 3. Mean stress in aluminized 2.5 micron Mylar™ as a function of absorbed dose and mean stress degradation of the sail material due to 1 year of shelf-life aging.

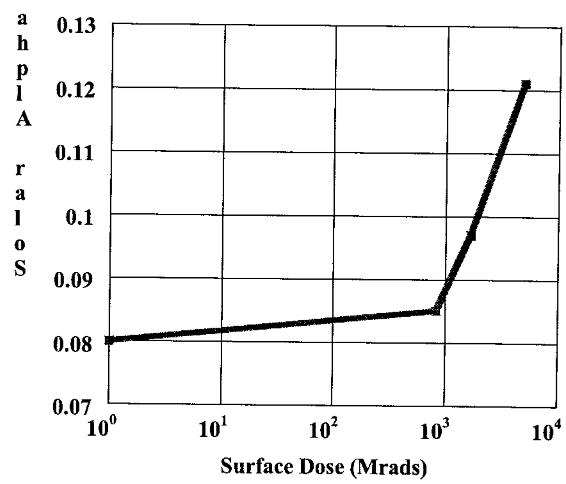

Figure 4. Solar absorptance in aluminized 2.5 micron Mylar™ as a function of surface dose.

A metalized CP1 material is being fabricated for characterization in the fall of 2001. A long term ultraviolet radiation exposure is scheduled to begin, also in early fall, 2001. Thus far, the materials to be evaluated are aluminized 2.5 micron Mylar™, metalized 0.9 micron Mylar™ and metalized CP1.

MSFC is working to produce a Gossamer / Solar Sail environmental requirements document. This document will aid Sail designers by defining the space environment constituents that are specifically influential to sail performance and lifetime performance. MSFC is also working to produce a micrometeoroid environment definition and model specifically tailored to solar sails. This environment definition will focus on defining the micrometeoroid environment of interplanetary space. This activity is lead by MSFC with participation by JSC, JPL, and GRC. The environment requirements document is scheduled to be complete by the end of FY02, and the micrometeoroid model is scheduled to be complete by the end of FY03.

MSFC is working with LaRC to perform dynamic analysis of sails. A dynamic analysis model is being produced using a 10 meter sail. Experimental results will be used to validate the model. A 100 meter sail will be analyzed, using the dynamic analysis model to perform parameter studies. Post-buckling static analyses will be performed and post-buckled shape and stiffness modal analyses will be studied. In addition, film attachment effects, boom compression loads and catenary effects are being investigated, specifically for a square sail configuration.

II. European Programs

The University of Glasgow has been developing a new mission concept for a small, low performance solar sail under contract to the Lockheed-Martin Corp[19,20]. The GEOSAIL mission uses a 40x 40 m solar sail to maintain a small space physics payload in the geomagnetic tail. Conventional geomagnetic tail missions require a spacecraft to be injected into a long elliptical orbit to explore the length of the geomagnetic tail. However, since the orbit is inertially fixed, and the geomagnetic tail points along the Sun-Earth line, the apse-line of the orbit is precisely aligned with the geomagnetic tail only once every year. Approximately 4 months of data can be acquired, with only 1 month of accurate data from the tail axis. To artificially precess the apse line of the elliptical orbit to keep the spacecraft in the geomagnetic tail during the entire year would be prohibitive using chemical propulsion Although the delta-v for apse-line rotation is large, only a small acceleration continuously directed along the apse-line of the ellipse is in principle necessary. For a solar sail, it can be shown that a characteristic acceleration of 0.14 mm s^{-2} is required for a 10 x 30 Earth radii orbit. Since the precession of the apse-line of the orbit is chosen to match that of the Sun-line, the sail normal can be directed along the Sun-line. This has significant operational advantages since such a Sun facing attitude can be achieved passively. The precession of a 10 x 30 Earth radii orbit is shown in Fig. 1. GEOSAIL is currently scheduled to undergo a NASA/JPL Team-X study later in 2001.

The University of Glasgow has also been developing a range of mission concepts under contract to the European Space Agency. Existing SEP mission concepts, such as the COLOMBO Mercury orbiter mission, have been considered and re-configured for solar sail propulsion. In the case of the Mercury orbiter mission it was shown that launch mass could be reduced by up to 50%, leading to lower cost launch. The use of a solar sail was also shown to provide a range of end-of-life mission applications, including escape from Mercury and transfer to a close solar orbit, or return to Earth orbit as a pathfinder for future sample return missions. In addition to these future mission concepts a separate study is evaluating a small solar sail (total launch mass 40kg) for the second of the ESA PROBA series of technology demonstration missions.

European hardware activity has centered on the planning for an Earth orbit deployment test of a 20 x 20 m solar sail, similar to the DLR ground deployment test of December 1999. The in-orbit deployment test would use a Volna launch vehicle to deliver to stowed solar sail to a ~800 km near polar orbit. Imaging of the deployment would be performed by a number of cameras and additional engineering telemetry recovered and analysed post-flight. The test would utilise the DLR composite booms used in the 1999 ground test.

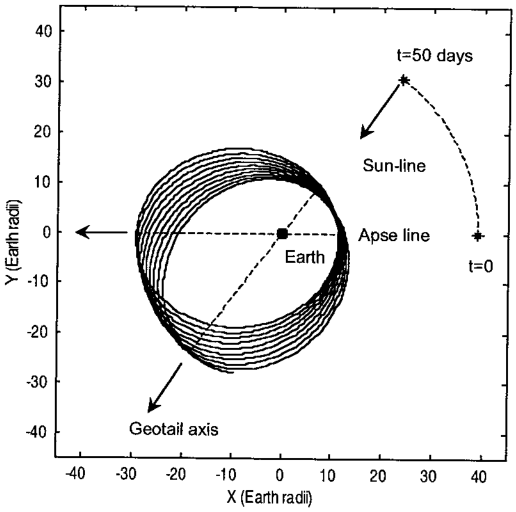

Figure 5. 10 x 30 Earth Geosail orbit.

III. Mission and System Studies

The greatest impediment to the application of solar sails for space missions is the lack of any complete flight experience. Below are discussed flight demonstration missions under study: a concept under development at Carnegie-Mellon, Hoop sail mission, Encounter, and the Planetary Society solar sail technology validation missions.

III(a). Carnegie Mellon University

Carnegie Mellon University (CMU) is building solar sail models and designing a low-cost sail validation mission called Solar Blade. The program at CMU is funded collaboratively by USAF, NASA, The Space Studies Institute, The FINDS Foundation, Lunacorp, Radio Shack and Carnegie Mellon University[18].

CMU's flight concept combines nanosat technology with a small sail to dramatically reduce spacecraft payload mass. A team headed by Carnegie Mellon University is designing a 80-meter diameter heliogyro solar sail for this mission concept. The schedule for the Solar Blade experiment calls for a launch in late 2001 – early 2002 as a secondary payload with a release altitude of 10,000 km or higher.

The Solar Blade Heliogyro has the appearance of a Dutch windmill and employs sail control akin to a helicopter. Four solar reflecting blades, 40 meters long by 1 meter wide and constructed from ultrathin polyimide film, are attached to a central spacecraft bus and are pitched along their radial axis. Embedded Kevlar and battens provide added stiffness and resistance to tears. The satellite uses collective and cyclic pitch of these solar blades relative to the sun's rays to control attitude and thrust. The spacecraft weighs less than 7 kilograms, and, when stowed, is a cylindrical package 0.4 meters in diameter and 1.2 meters high. The total launch mass, including the stowage vehicle, is 35 kilograms.

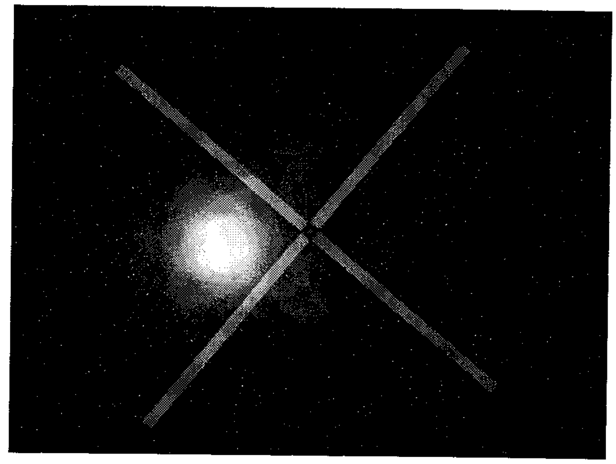

Figure 6. Conceptual drawing of the CMU Solar Blade sailcraft.

The Solar Blade and its accompanying stowage vehicle launch as an integrated package. After release from the launch vehicle, a propulsion unit on the stowage vehicle detumbles the spacecraft and points it toward the Sun. While maintaining a lock on the Sun, the blade roll holders deploy, and the propulsion unit spins up the spacecraft to 60 revolutions per minute. Then, the blades feed out in a controlled, balanced manner. During deployment, Solar Blade slows to its operating spin rate of 1 rpm.
A panospheric camera mounted on the stowage vehicle films the entire deployment. Then, the stowage vehicle and Solar Blade separate (Figure 6), leaving the stowage vehicle to slowly deorbit. The spacecraft will demonstrate attitude precession, spin rate management, orbital adjustment, and station

keeping in Earth orbit for a month, then Solar Blade will attempt an outward spiral trajectory.

The Laboratory of Atmospheric and Space Physics (LASP), located at the University of Colorado Boulder, provides the satellite detumbling, Sun-acquisition, and spin-up design, which consists of a bank of cold gas thrusters, a Sun presence diode, a Sun crossing diode, and bang-bang control logic incorporated in a PC board. Their system resides on the stowage vehicle. Solar Blade and the stowage vehicle utilize amateur radio band frequencies in the range of 1 to 10 GHz, at a power of up to 10 Watts.

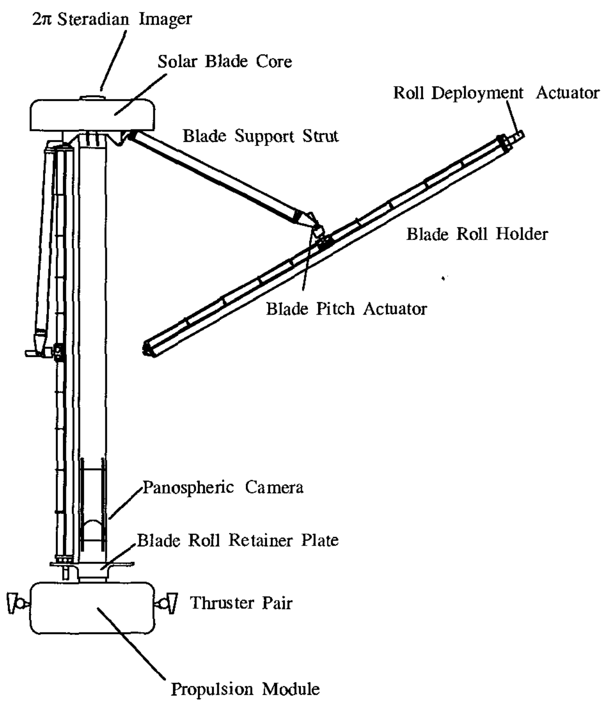

Figure 7. Solar Blade/Stowage Vehicle Package with Major Components Labeled.

Laboratory tests of blade deployment verify the theory behind the actuation of long, thin blades. The figure below shows test results of a scaled-down blade inside a large spinning box. The behavior of the blade during pitching maneuvers shows the tip of the blade following in-step the motion of the blade root, indicating proper actuation. Further tests including photogrammetric measurements inside a vacuum chamber will allow complete verification of analytical models.

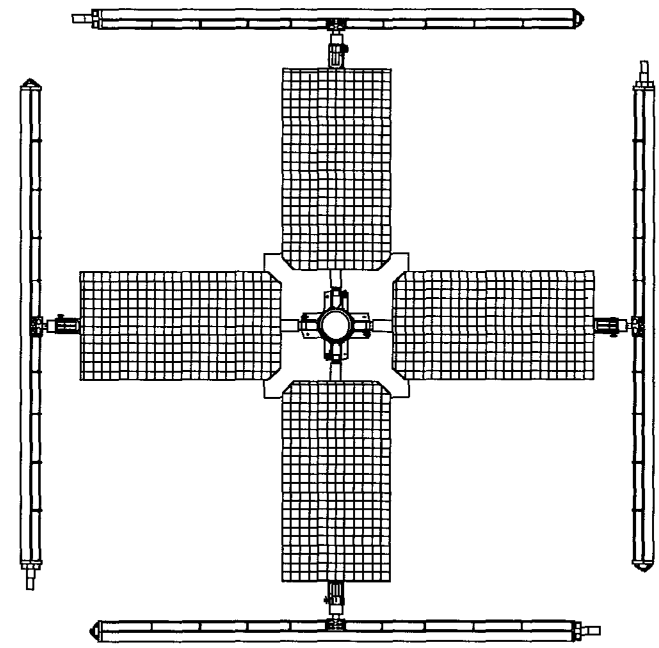

Figure 8. Face-on view of Solar Blade core after deployment. For clarity, the blades are not shown Unfurled.

The Solar Blade spacecraft can accommodate adapters from various launch vehicles, as long as the interface is similar to commercially available interfaces. It does not require a telemetry passthrough, but will use it if it is available. Solar Blade is currently designed to be compatible with an Ariane secondary payload fairing.

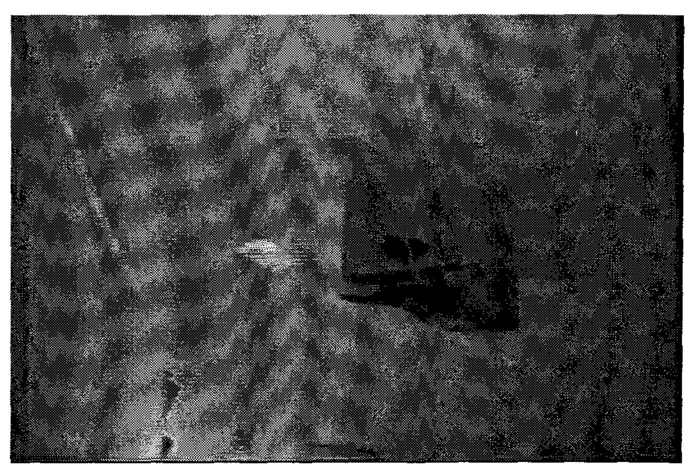

Figure 9. Scaled-down blade in spinning room. Blade extends from lower center of the picture.

III (b). Encounter

Team Encounter is a unique space venture to build and launch an interstellar spacecraft to carry the messages, drawings, photos and biological signatures (micro hair samples) of millions of Earth's inhabitants outside of our solar system. The Team Encounter Deep Space Probe will carry this payload, like a "cosmic message in a bottle" using a solar sail for primary propulsion. Team Encounter successfully concluded the Spacecraft Conceptual Design Review, and plans for several technology validation tests before launching the mission in the third quarter of 2003.

The Deep Space Probe will be used to achieve Earth escape, then the solar sail will be deployed. Plans call for a Shuttle space test of the spacecraft two years before launch, and a subscale version of the solar sail will be tested sometime in early 2003. The spacecraft will be built around a "Bitsy-SX Spacecraft Kernel" by AeroAstro, Inc. and will measure 60 x 60 x 80 cm to fit the secondary payload requirements for an Ariane piggyback launch. The spacecraft and sail will together weigh approximately 104 kg. The design details for the sail are discussed below.

The sailcraft conceptual design developed for the Encounter 2001 mission is shown deployed in Figure 10 and packaged in Fig 11. The sail parameters are summarized in Table 1. Once on orbit and upon being positioned by the carrier vehicle, the canister is discarded and the sail is deployed over a one-hour period of time. Deployment is accomplished by inflating the conical telescopically packaged booms. As the booms deploy, the sail is unfolded and deployed. This method of boom packaging was chosen because it provides precise deployment control with NO additional mass. The booms are kept warm during deployment by a small infrared heater at the base of each boom. Once deployed, the boom is allowed to rigidize by passively cooling below the glass transition temperature of the laminate resin. Rigidization is expected to take approximately 30 minutes. At this point the sail is completely deployed and the carrier vehicle is separated from the sailcraft.

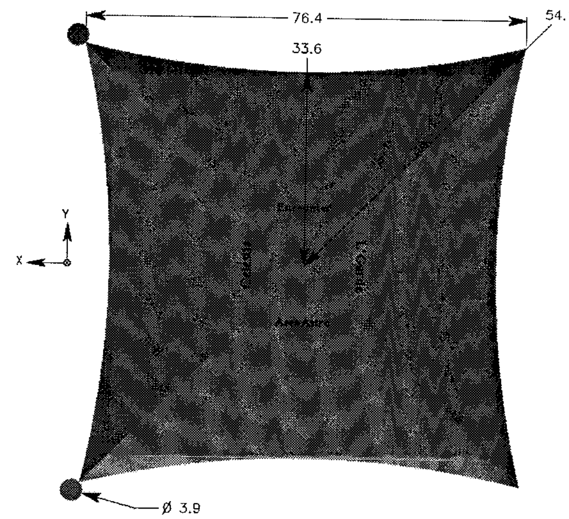

Figure 10. Deployed sail. All dimensions in meters.

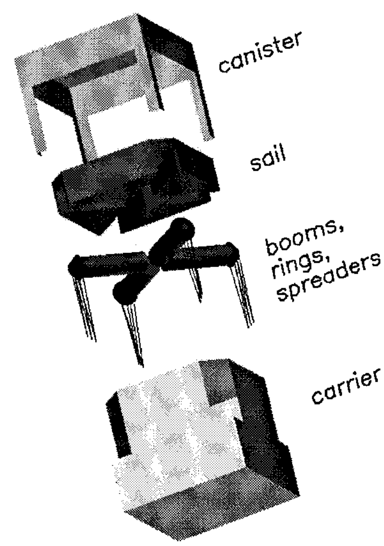

Figure 11. Packaged sailcraft

The sailcraft is required to achieve solar system escape (in any direction) within 3 to 5 years with its 3 kg payload. In order to achieve this, the sailcraft must achieve a lightness factor (measure of the fraction of solar gravity offset by solar pressure forces when the sail is normal to the sun's rays) of greater than 0.38 and an areal density of less than 3.5 g/in^2 and reflectivity greater than 90%.

TABLE 3.2-1 SAIL PARAMETERS

Surface Area	(m^2)	4907
Effective Propulsive Area	(m^2)	4797
Mass / Effective Propulsive Area	(g/m^2)	3.33
Lightness Factor @ beta=0°		0.4110
Tab Angle;	(degrees)	5.2
Sail depth	(m)	0.8
Sail Substrate Thickness	(µm)	0.9
Isotensoid Stress	(Pa)	6895
Frontside Al Metallization	(A)	300
Total Reflectivity "r"	%	90
Propulsive Reflectivity "Rp"	%	78
Backside Cr Metallization	(A)	200
Operational 1AU Sail Temperature	(°C)	-38
Boom Base Diameter	(cm)	9.5
Tip Diameter	(cm)	3
Average Boom Linear Density	(g/m)	14.1
Boom Compressive Load	(N)	1.7
Boom Modulus	(Mpa)	13,790
Minimum Structural Safety Factor		4.2
Tip Vane Mass, ea (w/o Actuator)	(g)	118

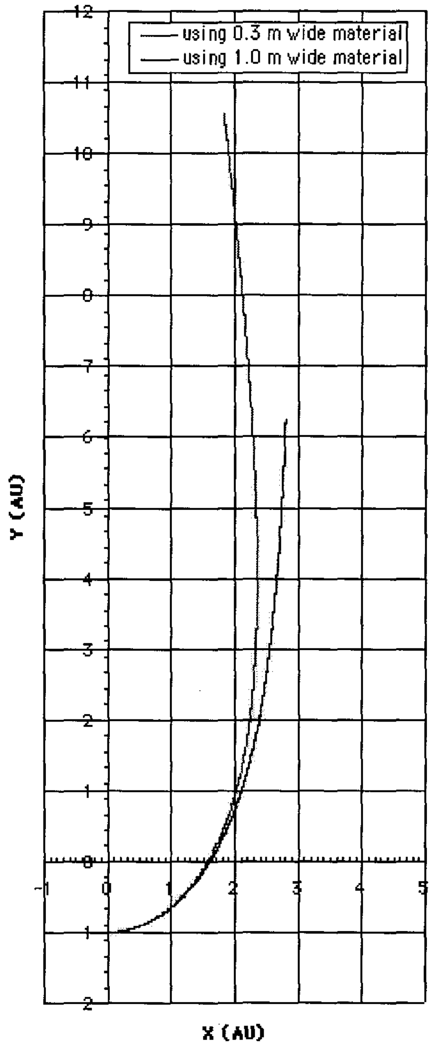

Figure 12. Sailcraft trajectory

The sailcraft escape trajectory (Figure 12) is achieved by giving the sail a trim angle of 25° with respect to the sun. The sail is passively stabilized in the pitch and roll axes by use of "tabs" that bend the sail booms such that the sail is bent away from the sun around its periphery (Figure 13).

The 25° trim angle is maintained by locating the 3.0 kg payload away from the center of the sail. This in turn moves the sailcraft center of mass away from the center of pressure. After 300 days, at which point the sailcraft trajectory is essentially radially away from the sun, the payload mass is moved to the center of the sail. This brings the sail to a zero degree trim angle and makes maximum use of the solar pressure to increase sail velocity along the desired trajectory.

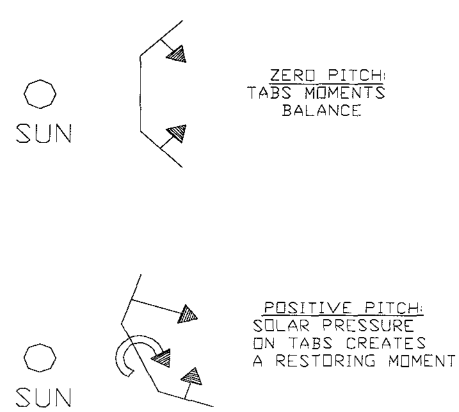

Figure 13. Passive stabilization design for the sail.

Whereas the sailcraft is passively stabilized about the pitch and roll axes, this is not the case with the yaw axes. Since it is not possible to passively stabilize the sail about the yaw axis, it is necessary to provide yaw control vanes at the tips of two of the booms. These vanes are each 3.9 m in diameter. The yaw sensor (star camera) measures the sailcraft orientation relative to a fixed star field. When the sensor detects a yaw error, a command is sent to the yaw vane actuators (paraffin rotary actuators) to rotate the vanes and null out the yaw error. Yaw control is discontinued after the 300-day maneuver because the pitch angle becomes zero degrees eliminating the need for yaw control.

III(c). Planetary Society Sail Demo

The Planetary Society and Cosmos 1 Studio, an internet media venture, have teamed together to validate solar sail technology. The program plans for a sub-orbital flight of a subscale sail in July 2001 and a full-up sail mission, called Cosmos 1, in the fall of 2001.

The sub-orbital flight scheduled for launch in mid-July 2001 will validate the deployment dynamics and basic design of the sail. A 2-bladed sail 30m in diameter has been built at the Babakin Space Center (located in Moscow, Russia), and packaged in a container for launch from the Barents Sea north of Murmansk on a converted ICBM. The sail is comprised of two triangular blades approximately 10.5 m wide and 15 m long, with inflatable tubes for structure and PETF film (a Russian form of Mylar) 5 μm in thickness for the sail reflector. The sail package will be released at an altitude of approximately 400 km, whereupon the sail tubes will be inflated with cold gas from a gas supply located at the hub of the package to a pressure of approximately 1 mbarr. The process to fully deploy the sail is expected to require approximately 60 seconds. Sail deployment will be imaged with a digital camera and pressure sensors placed at various locations in the sail blades will aid in determining success of this deployment experiment. After a total flight time of approximately 15 minutes the science package will then separate from the sail, landing ultimately in the Kamchatka peninsula (Figure 14).

The suborbital test was originally scheduled for a mid-April 2001 test but was postponed when the spacecraft was damaged during preflight check-out on April 9, 2001. Damage to the sail and spacecraft was expeditiously repaired and the team is awaiting finalization from the Russian navy for a time slot for launch, expected in mid-July 2001.

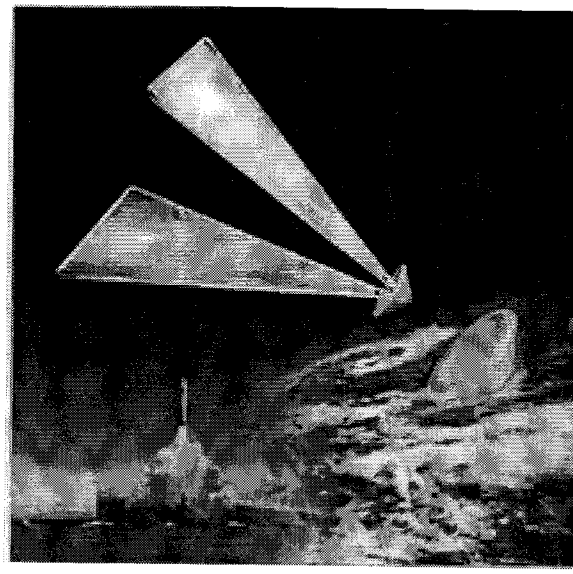

Figure 14. Planetary Society sail deployment validation test.

Following the deployment validation will be a full-up sail mission, called Cosmos 1, scheduled for launch some time in the fall of 2001. An 8-blade sail based on the 2-blade design described above (Figure 15) will be packaged in a 40-kg spacecraft aboard a Volna rocket (a converted SS-N-18 submarine-launched ballistic missile) and placed into near-polar orbit at an altitude of approximately 850 km and an inclination of 78 degrees. The sailcraft will then spin up to a rate of 10 rad/sec (approximately 1.6 revolutions per second), the sail blades will be pressurized, and the sail will be fully deployed in approximately 60-200 seconds. Once fully extended, the rotation of the sailcraft is stopped and the sail blades can be pitched up to 1 degree per second to control the direction of flight. The 8 sail blades will be configured in two decks of 4 blades each with each blade spaced 45 degrees apart. Once fully deployed the sail will have a diameter of 30 m and an areal density of approximately 11 g/m^2, and in fact the sail may be visible from the ground. Telemetry

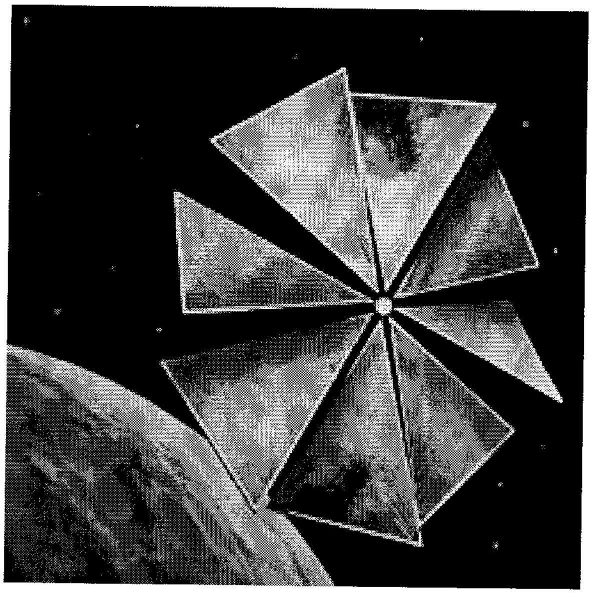

Figure 15. 8-bladed Planetary Society sail based on Babykin Space Center design concept.

will be received both in Russia and the US. Mission analysis indicates that this sailcraft can achieve Earth escape and sail to the moon in under 2 years, however the mission plan at present calls for a 3-month mission that validates control, operations and orbit-raising.

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